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Continuous Buckypaper Manufacturing Process: Process Investigation and Improvement

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CONTINUOUS BUCKYPAPER MANUFACTURING PROCESS: PROCESS INVESTIGATION AND IMPROVEMENT

By

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ABSTRACT

Carbon nanotubes have excellent electrical, thermal, and mechanical properties as determined theoretically and experimentally. Their properties make them great candidates for use in a number of applications ranging from lightning strike protection for airplanes to computer heat sink. However, carbon nanotubes are incredibly small, with diameters as small as 1nm and just a few micrometers long. The nanoscale size makes carbon nanotubes impractical to be used individually for many industrial purposes, thus methods have been developed to fabricate macroscale networks of carbon nanotubes. The carbon nanotube networks, also called Buckypaper, have showed mechanical, thermal and electrical properties inferior to those of individual nanotubes. Extensive work has been conducted to develop and optimize suitable production methods of producing high quality Buckypaper and enhance their properties. Many approaches are capable of producing a carbon nanotube network, but most are not able to scale up for industrial applications due to size and production rate limitations.

This research focuses on two aspects of Buckypaper manufacturing improvements. The first is to test 90 mm samples of Buckypaper disks to determine the impact of each processing parameter on the quality and properties. Statistic analysis was used to reveal the effect of processing parameters. Utilizing these results, a long sample of Buckypaper was produced and examined for property and quality consistency along the sample length, using modified customer-made continuous filter devices. Additionally, long samples with larger width were produced to demonstrate production rate of continuous Buckypaper manufacturing.

Through this research it was found that the electrical conductivity of the Buckypaper was affected positively by an increase in sonication pressure. Additionally, increases in pressure and increase in power of sonication led to an increase of Buckypaper strength. Strength and electrical properties of the continuous Buckypaper were considered consistent throughout the length. These results provide essential understanding of the continuous Buckypaper manufacturing process.
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1. INTRODUCTION

Carbon nanotubes have excellent electrical, thermal, and mechanical properties as determined theoretically and experimentally. Their properties make them ideal for use in a number of applications ranging from lightning strike protection for airplanes to computer heat sinks(1). However, carbon nanotubes are incredibly small, with diameters as small as 1nm and just a few micrometers long. The nanoscale size makes carbon nanotubes impractical to be used individually for industrial purposes, thus methods have been developed to fabricate macroscale networks of carbon nanotubes. The carbon nanotube networks, also called Buckypaper, have proven to have mechanical, thermal and electrical properties inferior to those of individual tubes. Extensive work has been conducted to develop and optimize suitable production methods. Many approaches are capable of producing a carbon nanotube network, but most are limited to research applications and their production methods are insufficient for industrial scale manufacturing due to size and production limitations.

To use CNT to their full potential large quantities of consistent quality BP needs to be produced. At High-Performance Materials Institute (HPMI) at Florida State University extensive research has been conducted on batch production of Buckypaper, but the resultant BP size was restricted by sealed chamber manufacturing equipment. Recently, a continuous method of continuous fabrication of BP was developed at HPMI (2)(3). In this research a comprehensive study on the impact of varying the processing parameters of BP continuous manufacturing process has been carried out. Additionally, demonstration of consistent quality and major properties of continuous Buckypaper (CBP) was conducted to prove the potential of CBP for industrial applications.
2. OBJECTIVE

The objective of this work is to determination the correlation that exists between the Buckypaper processing parameters and the response variables of: thickness, strength, modulus, strain, and electrical conductivity and develop a model relating processing parameters to the response variable. From the model, improved processing parameters will be selected and applied for production to the 1.5” CBP filter. The 1.5” CBP filter is modified to improve production rate and consistency. Additionally the concept of increasing production rate by increasing filtration area is examined and a wider CBP filter with integrated washing and harvesting sections are developed. To demonstrate the continuous production capabilities of the CBP filters, continuous strips are produced.
3. LITERATURE REVIEW

3.1 Introduction to BP Manufacturing

There are many methods for producing BP, also referred to as carbon nanotube networks, sheets, and films; some methods are designed to create high strength networks, while others focus on electrical, thermal, or optical properties. Research has been conducted within many research facilities and industries to develop various BP materials. A comprehensive review of BP manufacturing was created by Park, Lin, et. al. detailing accomplishments in research and manufacturing of BP materials up to 2006(1). Therefore, only novel research that was conducted on BP production after 2006 will be discussed here. Dr. Smalley’s work which represents the first BP produced in 1998 is the only exception. A brief review of the recent accomplishments of BP manufacturing will be compiled. HPMI efforts will be discussed in detail with the emphasis on the contributions to BP technical development at different phases in the previous researches.

3.2 Progress of BP Manufacturing

3.2.1 First Buckypaper Fabrication

The first carbon nanotube network or Buckypaper, was created in 1998 by Smalley et. al. in an attempt to test the purity of manufactured carbon nanotubes(4). Carbon nanotubes were functionalized with surfactant Triton-X 100 and then sonicated to break up larger bundles of the carbon nanotubes. The resulting suspension, named because the nanotubes were suspended in aqueous solution, was vacuum filtered onto a membrane of unspecified maker and pore size. Once the paper was dried it was washed in methanol to remove surfactant and the carbon nanotube network was removed from the membrane. Smalley et. al. coined the name “bucky paper.” An SEM image of the first Buckypaper, provided in Figure 1, shows the nanotube network.

This sample was only created for testing nanotube physical property purposes, not for BP manufacturability study. Since this sample’s creation many more innovative approaches to make Buckypaper have been studied and reported.
3.2.2 Highly Oriented Carbon Nanotube Papers Made of Aligned Carbon Nanotube Arrays

Dr. Smalley’s method required the functionalizing of the nanotubes, which, ultimately leads to a decrease in purity as it is almost impossible to completely remove surfactant from BP samples. A proposed method to tailor the growth of the nanotubes for the network fabrication application was reported (5). For an example, as depicted in Figure 2, aligned multiwalled carbon nanotubes (MWNT) arrays or forests were grown on a 10 cm diameter silicon substrate using carbon vapor deposition (CVD). The MWNT arrays were then covered with a microporous membrane and a cylinder was rolled over top of them with constant pressure. This was done multiple times, taking advantage of the van der Waals attraction between the nanotubes to create a network. The resultant nanotube paper was easily peeled off from the substrate and the paper and membrane were soaked in ethanol to separate the BP from the microporous membrane.
The resultant nanotube paper is strong, but flexible and features ropes with approximately 15nm diameters. The paper thickness was measured at an average of 26 μm and had a thermal and electrical conductivity of 153 W/mK and $2.0 \times 10^4$ S/m respectively (5). Researchers stated that one application of interest for this material would be to use it as a supercapacitor electrode. An image as shown in Figure 3 further emphasizes the strength and flexibility of their product; typically Buckypaper is very brittle and incapable of withstanding even moderate deformation.
The increased strength and flexibility of this Buckypaper make it very attractive for mechanical applications. However, the process has only been published using MWNT, which maybe are electrically inferior to SWNT. Additionally, the CVD process restricts the size of Buckypaper that can be manufactured.

3.2.3 Self Assembly of Single-Walled Carbon Nanotubes into a Sheet by Drop Drying

In this method, SWNTs were mixed with surfactant and water and dropped onto a glass substrate. The drops were allowed to dry and a “crust” of nanotubes was left. Analysis showed that each bundle was of approximately 10 SWNTs; researchers attributed this low number to the spontaneous self assembly of the SWNTs during drying. This method is believed to be capable of producing thin (100nm), optically transparent, conductive films and coatings. Before this can be realized, though, the mechanical properties must be improved enough for electrical property measurement. Also, surfactant in the drops will need to be burned or washed off. In Figure 4 an SEM image of one drop is show. The sample was coated with gold causing an increase in thickness appearance of the CNT strands.
3.2.4 Solution-Deposited carbon Nanotube Layers for Flexible Display Applications

In this approach, a suspension of CNT was prepared and sprayed on a coated plastic or glass substrate with a conventional airbrush (7). The substrates had been coated with an adhesion to increase the otherwise poor adhesion properties of CNTs. Afterward, the material was coated with polyimide to further increase adherence and fill in gaps. An image of the network with polyimide coating is shown in Figure 5.
The optical transmittance of the film over the visible wavelength was shown to be acceptable, however, when compared with Indium Tin Oxide, a popular material used for displays, the nanotube film performed poorly. Researchers anticipate that by reducing bundle sizes and increasing smoothness of the surface of the film increased optical properties can be achieved. This process creates films that could be ideal for creating lightweight, flexible displays if transmittance can be improved. The use of a foreign adhesion may result in less than optimal transmittance. Additionally, researchers plan to use centrifugation to remove large bundles from suspension, a lengthy and expensive process that will ultimately limit large scale production.

3.2.5 Preparation of a Carbon Nanotube Film by Ink-jet Printing

Similar to the drop method, a suspension of carbon nanotubes was created and placed into a commercial ink-jet printer (8). The nanotube suspension were printed onto a transparency sheet using multiple passes to increase the density of the strips, as shown in Figure 6. Measurements of the electrical resistivity show a decrease as the number of prints increases. The films were created 100 nm thickness using 20nm diameter MWNTs. This method has not been extensively studied, though, and the strips were shown to have very poor mechanical properties.
The printing process creates a method with which CNT can be deposited and formed into a specific pattern, with some degree of control over the resistivity of the paper. The low mechanical properties make it impossible to remove from the substrate, and therefore the current process maybe is only suitable for scientific research purposes.

3.2.6 Nanocomp Large Buckypaper

Nanocomp created the largest sheet of BP in February of 2008(9). The sheet measured 3’x6’ The propriety manufacturing process has yet to be disclosed to the public. The company states that it is capable of producing the sheets at a rate of one sheet per day, consistently. Plans were underway for large scale manufacturing by the middle of 2008(10). An image of their BP is shown in Figure 7. However, the feasibility to produce infinitely continuous products is not clear.
3.3 Literature Review Conclusions

From the different studies on carbon nanotube network production it is apparent that mechanical properties are still lacking in most cases. In the instances where mechanical properties are improved, though, superior thermal and electrical properties are not seen. Of the processes reviewed only one has the capability to be semi-continuous with current production methods, the process involving drawing from a carbon nanotube forest. The only process claiming to have potential for continuous production is the BP production at Nanocomp. The proprietary production information and quality consistency of their products are unknown. The lack of a definitive, high quality and truly continuous production method of Buckypaper is still a major barrier for industrial applications of nanotube products.
4. HPMI BUCKYPAPER PRODUCTION

HPMI has been studying carbon nanotubes and Buckypaper fabrication since 2001. Multiple projects have been conducted. So far there exist two distinct processes for BP production, the batch suspension and batch filtration production method, and the more recent continuous suspension and continuous filtration production method. Both of these methods will be discussed and key points of research completed will be presented.

4.1 Buckypaper Production

4.1.1 Batch Production Method

The batch production method produces one sheet of Buckypaper, random or aligned, with a size of up to 11”x23”. The production steps are outlined as follows:

- Mix the nanotubes with Tritan-X 100 surfactant and water and sonicate with sonication tip in open air. Dilute with water and resonicate with sonication tip in open air until desired concentration is met.
- Filter the suspension through a microporous membrane, this can be done in a flat filter to produce random BP or in a cylindrical filter placed in a magnet for aligned BP.
- Dry and separate the BP from the membrane.
- Soak the Buckypaper in isopropyl to remove the surfactant.

4.1.2 Continuous Process Production Method

The continuous process is capable of producing Buckypaper strips of either random or aligned SWNTs. The production steps are as follows:

- Mix the nanotubes with Tritan-X 100 surfactant and small amount of water and sonicate briefly in open air with a high ratio of nanotubes to water.
- Dilute the concentrated suspension with water and sonicate.
- Filter the suspension through a continuous microporous membrane; this is done simultaneously to the suspension production. The system can be placed in a magnet for aligned BP, or random BP can be produced without the magnet.
- Dry and separate the BP from the membrane.
- Soak the Buckypaper in isopropyl to remove surfactant.
4.2 BP Research at HPMI

For the past several years the research conducted by HPMI researchers has improved the production process and quality of Buckypapers. A review of the work of four projects provides some of the most relevant research to address CBP production.

4.2.1 BP Network Buildup and Washing Techniques

The flow rate of residual suspension filtered out when creating Buckypaper was studied to determine if there was a correlation between the time of filtering and the amount of water filtered(11). This research detected a dramatic decrease in filtration rate as time increased, indicative of a dense network buildup of nanotubes. As the nanotubes built up, the pore size of the membrane was no longer a controlling factor to control filtration speed; instead the pore size of the formed nanotube network becomes the restriction. In Figure 8 the filtration rate vs. liters already filtered is shown. This graph shows that as more liters of water were filtered the time for filtration increased due to the nanotubes being deposited onto the membrane.

![Figure 8: Number of liters filtered vs time taken for each liter (11).](image)

In addition to measuring filtration rate for random Buckypaper, the research was also done on the relationship of filter time for magnetically aligned BPs. The results, in Figure 8 and Figure 9, show that there is only a slight increase in filtration time from random Buckypapers compared to aligned Buckypapers. This is attributed to the more ordered and dense structure of the nanotubes in the aligned Buckypaper (11).
The thickness of batch production Buckypapers was also measured to determine thickness uniformity of the papers both individually and as a collection (11). Figure 14 shows the statistical means of each paper along with standard deviation. An analysis on whether or not the papers were statistically consistent was not conducted.
An examination of the thickness of individual Buckypapers proved that thickness varied depending on the position of the paper during filtration (11). In Figure 15 the thickness is shown to increase from Zone 1 to Zone 3, where Zone 3 was located at the bottom of a cylindrical, stand-up filter. This thickness was attributed to gravity, however, the rope diameters at these locations were not compared to assess whether agglomerated particles composed the majority of the material at the bottom of the filter.
After measuring mechanical data on the Buckypapers, the focus was turned to the residual surfactant still presented after filtration. An analysis of various washing methods for the removal of surfactant was conducted. It was determined that soaking the paper in isopropyl for 2 hours sufficiently removed most of the Triton-X 100 used to functionalize the carbon nanotubes.

The studies conducted by Lin identified that a network buildup of nanotubes over time existed. The buildup decreased pore size for water to pass through and created slower CNT buildup, thus a linear relationship between CBP thickness and time cannot be expected. Additionally, the research conducted on BP washing established an optimal washing time from which a consistent washing method was established throughout HPMI for all BP fabrication.

4.2.2 Effect of Sonication Power on Nanotube Diameter and Relationship of Magnetic Force and Electrical Conductivity

In this research the nanostructures and specific surface area were studied based on types of materials used, including MWNT, SWNT, and carbon nanofiber (CNF) and processing parameters (12). The parameters included sonication power, surfactant amount, isopropyl amount used for cleaning, and the rope sizes of the raw materials. The conclusion was the higher sonication power leads to smaller nanotube rope size, which, in turn, leads to higher surface area of Buckypapers.

The resistivity of SWNT Buckypaper was correlated to the diameter of the ropes within the BP samples (12). Also, a comparison between the Tesla under which the paper was subjected to and the conductivity was carried out. It was found that as the diameter of the SWNT
rope increased, the conductivity decreased drastically. Also, there is a value between 8.5 T and 17.3 T at which the conductivity of the sample did not increase with the increase of magnetic field strength.

4.2.3 Initial Continuous Buckypaper Filter Manufacture

Limitations for manufacturing in the batch process of Buckypaper lead to the development of a continuous filter and process (3). The first filter was capable of producing Buckypaper averaging 5μm in thickness, had a normal distribution of nanotube ropes, averaged 11.92 nm diameter SWNT ropes, and had an electrical resistivity of $5.83 \times 10^{-3}$ ohms/cm. Production rates were limited to 3.768 inches per hour and the width was 1.5 inches. The conceptualization and creation of this filter inspired further improvements for the process.

4.2.4 Continuous BP Manufacturing and Quality Measurements Using UV-VIS Spectrometer

Safety concerns with batch production of suspension included loud noises associated with the long term use of open air sonication devices and raw, dry nanotube inhalation. These issues were addressed by the implementation of a newly developed sonication system. In addition to increasing safety, continuous suspension production was achievable. The continuous process can realize on-time supply of fresh suspension for Buckypaper production. The system also allowed for the introduction of pressure during sonication and greatly increased production rates. The study was conducted and showed the addition of pressure increased the aspect ratio of the nanotube compared to using batch sonication method.

The quality of the suspension dictates the quality of the final Buckypaper (2). Analysis on the suspension was typically conducted of dried suspension samples using the Atomic Force Microscope (AFM) and a program developed by SIMAGIS for measuring nanotube rope diameter. In this study, the research was conducted using a new method: wavelength absorption as per a UV-VIS Spectrometer. An experiment was first conducted on a sample of suspension where the UV-VIS measurement took sample data of wavelength every 100 minutes. It is known that after sonication nanotubes in suspension will re-agglomerate, or that the nanotubes will bundle together as time increases. These bundles cause lower aspect ratios and poor mechanical properties of the resultant Buckypaper. The study verified that the output data from the UV-VIS Spectrometer shows that as time increases, the wavelength height decreases. This was assumed to be related to agglomeration, though further researches on various aspects are still required.
A metric was utilized for determining the quality of the suspension based on peak height and width, where a taller peak and a smaller width provided a more desirable dispersion (2). This can be visualized in Figure 13 where the tallest, thinnest peak is after the first 100 minutes after sonication processing. This method of measurement was applied to samples testing the effects of pump rate, pressure, flow rate and orientation of two independent flow cells. This experiment was originally run as a screening experiment to remove definitively insignificant factors, however, it was found that the number of experiments was too small and no factors could be removed without risk.

![Figure 13: UV-VIS measurements for suspension absorption over time(14).](image)

Further work was also conducted to improve the continuous filter process. After extensive testing and remanufacturing a CBP filter prototype was completed that was capable of producing a finite strip of Buckypaper with statistically uniform thickness throughout.

The research conducted by Rodriguez established a continuous suspension production method for Buckypaper production at HPMI (2). The continuous production of suspension was seamlessly integrated with an updated CBP prototype. Additional experiments using the UV-VIS spectrometer allowed for a graphical representation of agglomeration over time, further emphasizing the importance of the continuous suspension production.
5. THE 1.5” CONTINUOUS BUCKYPAPER FILTER

5.1 Purpose

In order to utilize Buckypaper for large scale production and industrial applications large quantities of Buckypaper of reasonable size and consistent quality must be produced. The 1.5” continuous Buckypaper filter was developed by HPMI researchers as a method for producing random and aligned strips of continuous Buckypaper. Previously sizes of Buckypaper were restricted to 11”x23” within a flat filter which utilized pressure to deposit nanotubes onto a porous filter membrane. The current continuous filter prototype is capable of producing Buckypaper of theoretically unlimited length. Experimentation has resulted in successful strips of Buckypaper of random SWNT, aligned SWNT, random MWNT, and random CNF. However, there are some issues of current filter, which need to be further modified to improve quality consistency and production rate.

5.2 Machine Mechanics

In order to be utilized in a high powered magnet the 1.5” continuous Buckypaper filter was made of ABS plastic. The filter was developed as a vertical filter to allow for insertion into the magnet.

The CBP filter is then placed in the suspension container and suspension is pumped into the container directly from the flow cell. The vacuum pump is attached to a vacuum line through the center of the CBP filter and suspension is pulled through the filter membrane, depositing carbon nanotubes onto the filter membrane and removing deionized water and surfactant.

5.3 Improvements on the 1.5” CBP Filter

5.3.1 Pneumatic Motor Degradation Issues

The 1.5” continuous Buckypaper filter originally used a computer controlled, pneumatically operated gear machined from ABS plastic, shown in Figure 14. After regular use the ABS plastic gear began to degrade. To prevent further occurrence of this issue during testing an electronic motor was installed on the system to realize smoother and more consistent advancement.
5.3.2 Increase of Filtration Rate

Through a number of trial and error experiments HPMI was capable of producing 1.5” of CBP at a slow rate. Filtration was conducted with an electrical powered vacuum pump. The vacuum line system required a vacuum trap to prevent the deionized water and surfactant filtered through the filter membrane from entering the vacuum pump. During long experiments the vacuum trap was often filled to the capacity and emptied during production, which caused the Buckypaper production process to be halted for several minutes. Regular maintenance was conducted on the vacuum pump after each paper was manufactured. This regular maintenance would need to be conducted during production for Buckypaper of long lengths. Additionally, the amount of suspension filtered through a section of filter membrane was not consistent through time. A previous experiment conducted by Rodriguez showed that the thickness of the Buckypaper decreased along its length, as shown in Figure 15. After production it was found that the HDPE plastic support had become clogged during filtration. The buckypaper thickness is related to the amount of suspension filtered through the membrane and indicates that filtration
time for each step is not a reliable and accurate parameter to reflect the filtration rate and control thickness of Buckypaper.

Figure 15: Time series plot of 5' strip of CBP produced by Rodriguez.(2)

In this research, through experimental testing by replacing the vacuum pump with the new vacuum system, a full vacuum was achieved. By using this method we were also able to measure the amount of fluid filtered through the filter membrane accurately. For an initial test creating a continuous strip of Buckypaper 1.4L of SWNT suspension was filtered onto the membrane for the first 5” of filter membrane. The average production rate was increased. This modification realized consistent amount of suspension filtration and more reliable thickness control of the resultant Buckypaper.
5.4 Initial Experimental Results

5.4.1 Thickness Measurements

Thickness measurements were conducted at 1 inch intervals along the continuous strip of CBP. At each one inch interval three measurements were taken 0.25” from each edge and at the center location of 0.75” from each edge. A diagram of sample measurement locations is shown in Figure 16.

![Figure 16: Measurements locations on the 1.5" CBP samples.](image)

Thickness measurements were conducted with a Heidenheim dial indicator (Id.Nr. 344992-01). The dial indicator is shown in Figure 17. The plunger is compressed by hand, lifting the measuring tool up. The sample is then placed under the measuring tool and the plunger is released slowly to lower the measuring tool down. The thickness is displayed on the digital readout to the 0.5 micrometer accuracy.

![Figure 17: Heidenheim dial indicator for thickness measurements.](image)
Measurements of thickness for a strip of SWNT Buckypaper showed that thickness with a low standard deviation.

The measurements for the CBP show some variation in thickness at certain locations. Thickness shows great sensitivity to parametric changes. Between locations 12 and 17 inch locations, the amount of fluid filtered was almost doubled, resulting in a dramatic increase in thickness and filtration time. At each location the average difference from the left, center, and right measurements was 1 micron with 0.352 standard deviation, indicating that there is little variation across the width of the filter during filtration.

Figure 18: Preliminary 5’ strip of CBP thickness measurements using the modified filter.
5.4.2 Electrical Properties

To test electrical resistivity the force current and measuring voltage (FCMV) method using the four-wire (Kelvin) connection scheme is recommended. The configuration is shown in Figure 19 and Figure 20.

![Figure 19. FVMC configuration for low-impedance devices.](image)

The resistance of the samples is determined by passing a known direct current, $I$, measuring the resulting voltage drop over the sample, $\Delta V$, and performing the division to get $R = \frac{\Delta V}{I}$.

![Figure 20. Circuit diagram for resistivity measurement experiments.](image)

The equipment and software used for testing electrical resistivity includes:

- Agilent 6631B power supply (8v/10A)
- Keithley 2002 MEM multimeters
- GPIB interface cards
- Labview 6.1 software

The test setup, including the four-wire fixture, is shown in Figure 21.
Tests were conducted on 1” samples of Buckypaper chosen at four locations: 7, 26, 32, and 56 inch locations on the CBP strip. Three samples were taken at each location and tested individually. The test samples were measured for width and thickness prior to testing. The test samples were placed in the four-wire resistivity fixed and tests were controlled and recorded by Labview. The bar chart displays the average electrical conductivity at each location as well as the standard deviation among the three samples at each location.

![Normalized Electrical Conductivity](image)

**Figure 22:** The electrical conductivity average and standard deviation of preliminary CBP

### 5.4.3 Tensile Properties

The tensile strength, modulus and failure strain were measured using a Dynamic Mechanical Analyzer (DMA) Q800 by TA Instruments, shown in Figure 23. The DMA operator measures the width and thickness of each sample strip. The strip is secured on the bottom of the fixture arm which is moved upward until the top of the strip reaches the top of the fixture where
it is secured. The program Thermal Advantage 1.1A is used to measure and record the tensile stress and strain. Results are given graphically for tensile strength, tensile strain, and modulus.

Figure 23: The Dynamic Mechanical Analyzer by TA Instruments.

DMA analysis was conducted on 1” samples of Buckypaper chosen at locations 15, 17, 38, and 47 inch locations on the CBP strip. Three samples were tested for each location. Figures 26-28 show the normalized data for fracture stress, fracture strain, and modulus for the 4 locations taken as well as the standard deviation within each set of locations.
5.4.4 Experimental Results Conclusions

The improvement of the 1.5” filter leads to improve quality consistency of continuous Buckypaper production. The electrical conductivity and mechanical properties of the initial CBP sample are fairly consistent, with the exception of failure strain which has a large standard deviation.
deviation for all measurements. Processing parameters still need to be investigated and optimized.
6. LONG BUCKYPAPER CONTINUOUS FILTER

6.1 Motivation

The 1.5” filter was designed as a vertical system for use in a high powered magnet. For random Buckypaper there is less restrictions. A flat filter with a larger filter area was designed to demonstrate whether consistency throughout a strip of Buckypaper was possible on a larger scale.

6.2 Long Continuous Buckypaper Filter Prototype

The initial prototype for the long CBP filter was made of ABS plastic and had side walls acrylic tall enough to hold 3L of suspension. The recessed filter area has two vacuum ports for removing fluid. The filter area was a recessed CNC design that precisely fit a porous HDPE for support and vacuum force dispersion.

It was found that at a value between 4-100 minutes was an adequate amount of nanotube network had built up to allow for harvesting of the Buckypaper. Recycled SWNT and MWNT suspensions were used to reduce cost instead of new SWNT suspension. Hence the resultant CBP samples were not characterized.

6.3 Long-II Continuous Buckypaper Filter Prototype

To address some issues with the initial long prototype a shorter width filter was developed. The filter was designed to realize three major functions: filter suspension to make Buckypaper, wash Buckypaper, and harvest Buckypaper.
7. DESIGNED EXPERIMENT STUDY UTILIZING 90 MM BUCKYPAPER DISK SAMPLES

Previous work by Rodriguez at HPMI showed processing parameters of amplitude, flow rate and pressure have an impact on the nanotube suspension within a continuous process system for suspension. A study of the impact of these parameters on Buckypaper thickness, electrical conductivity, mechanical properties, and nanostructure is essential for understanding their effects on final continuous Buckypaper products. In order to statistically determine the impact of each processing parameter a central composite design was created using the parameters shown in the Table 1(13).

Table 1: DOE ±Alpha values for 90 mm sample disk.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>- alpha</th>
<th>+ alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Amplitude, %)</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Flowrate (mL/min)</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>

A complete table of the design, as shown in Table 2, is sorted by the run order. For all following analysis the sample labels correspond to the run number order, not the standard order.

Table 2: Complete DOE for 90 mm sample disks.

<table>
<thead>
<tr>
<th>Standard Order</th>
<th>Run Order</th>
<th>Amplitude (%)</th>
<th>Flow Rate (mL/min)</th>
<th>Pressure (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1</td>
<td>70</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>52</td>
<td>160</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>52</td>
<td>340</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>52</td>
<td>160</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>5</td>
<td>70</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>70</td>
<td>250</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>52</td>
<td>340</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>70</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>14</td>
<td>9</td>
<td>70</td>
<td>250</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>70</td>
<td>400</td>
<td>10</td>
</tr>
</tbody>
</table>
The experiments were conducted using 90mm Nylon disk membrane from Sterlitech with pore size 0.45 microns. The sonicator was controlled by amplitude ranging from 0 to 100%, with 100% being full capacity. Flow rate is determined by the peristaltic pump. The flow rate of 100mL/min was chosen because it is the lowest flow rate capable of allowing for pressure buildup within the flow cell. Typical Buckypaper operations are conducted at 150mL/min, the high value of 400mL/min was greater than the maximum beneficial expected flow rate and was chosen to provide a good spread for flow rate values while still maintaining a reasonable size step between process parameter points. Pressure within the flow cell becomes unstable at values higher than 20PSI and has rapid, dramatic, uncontrollable increases in pressure at high pressure, therefore the highest pressure value chosen was 20 PSI, with the lowest being no pressure.

The setup of 90 mm disk sample fabrication is shown in Figure 27, including three 90mm filters connected to a peristaltic pump. Vacuum pressure on the samples fluctuated between 15 in-Hg and 25 in-Hg during filtration. All samples were created using 1.3L of suspension.
7.1 Thickness Measurements

Thickness measurements were conducted using the method described in Section 5.4.1 Thickness Measurements. A diagram of nine measurements taken for each sample, 8 around the perimeter and 1 at the center of the 90 mm sample is shown in Figure 28. For all 20 experiments the average thickness difference between the center point and the average thickness of the perimeter points is less than 0.1 micron.
A bar chart for the thickness of each sample is shown in Figure 29. The blue bars represent the average of the thickness measurement values and the error bars display the standard deviation between the 9 measurements taken for each 90 mm disk.

An ANOVA table was created using Design Expert 7.0 and used to develop a model for the relationship of the thickness and processing parameters. The ANOVA table, shown in Table 3, shows that the interaction between amplitude and pressure as well as the interaction between amplitude and flow rate have an impact on the thickness. Individually, pressure also has an impact on the thickness separate from the interactive impact with amplitude.

This may be related to nanotube dispersion quality affected by amplitude and pressure. Increases in power and amplitude are assumed to enhance nanotubes dispersion hence affecting
nanotube packing during deposition(2). An increase in pressure causes a decrease in thickness, while an increase in amplitude causes an increase in thickness.

One possible reason for this could be that increases in pressure may be debundling the nanotubes from large agglomerations, creating a thinner network allowing for the bundles of nanotubes to pack closer and filling in more voids. But the effect of amplitude is difficult to explain. It may be due to reducing aspect ratio, and hence reduction of van der Walls interaction and making loose network.

Table 3: ANOVA table for thickness of 90 mm sample disks.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4.57550</td>
<td>5</td>
<td>0.915099</td>
<td>5.60019</td>
<td>0.00485764</td>
</tr>
<tr>
<td>A-Amplitude</td>
<td>0.0467745</td>
<td>1</td>
<td>0.0467745</td>
<td>0.286249</td>
<td>0.601030</td>
</tr>
<tr>
<td>B-Flow rate</td>
<td>0.102926</td>
<td>1</td>
<td>0.102926</td>
<td>0.629881</td>
<td>0.440644</td>
</tr>
<tr>
<td>C-Pressure</td>
<td>2.22822</td>
<td>1</td>
<td>2.22822</td>
<td>13.6362</td>
<td>0.00241185</td>
</tr>
<tr>
<td>AB</td>
<td>0.843195</td>
<td>1</td>
<td>0.843195</td>
<td>5.16015</td>
<td>0.0394136</td>
</tr>
<tr>
<td>AC</td>
<td>1.35438</td>
<td>1</td>
<td>1.35438</td>
<td>8.28850</td>
<td>0.0121357</td>
</tr>
<tr>
<td>Residual</td>
<td>2.28767</td>
<td>14</td>
<td>0.163405</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>1.37530</td>
<td>9</td>
<td>0.152811</td>
<td>0.837439</td>
<td>0.615973</td>
</tr>
<tr>
<td>Pure Error</td>
<td>0.912371</td>
<td>5</td>
<td>0.182474</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>6.86317</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The $R^2$ for this statistic model is 0.66674, which is relatively high for experimentally tested data. The Adjusted $R^2$ is 0.547629, and the Predicted $R^2$ is 0.364864. High values of $R^2$ are desired, with the Adjusted $R^2$ and predicted $R^2$ values not being vastly different(14). The governing equation for thickness is:
Equation 1: Thickness model from 90 mm sample disk experiment.

\[ \text{Thickness} = 23.4020 - 0.08652 \times \text{Amplitude} - 0.01331 \times \text{Flowrate} - 0.3395 \times \text{Pressure} \\
+ 0.00020306 \times \text{Amplitude} \times \text{Flowrate} + 0.00387927 \times \text{Amplitude} \times \text{Pressure} \]

7.2 Electrical Conductivity Analysis

Electrical conductivity tests were conducted using the four wire test method from Section 5.4.2. For each disk sample three measurements were taken. The average conductivity of the samples is shown by the blue bars in Figure 30. The error bars represent the standard deviation among the three measurements for each of the disks.

Figure 30: The average electrical conductivity for 90 mm sample disk.

The ANOVA table is shown in Table 4. It shows that the only impact factor on the electrical conductivity of the Buckypaper is the pressure. The governing model shows that as the pressure increase, so does the electrical conductivity:
Equation 2: Electrical conductivity model from 90 mm sample disk experiment.

\[
\frac{1}{Electrical \ Conductivity} = 0.01456 + \frac{0.016877}{Pressure}
\]

Table 4: ANOVA table for electrical conductivity for 90 mm sample disks.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Sum of Square Mean</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2.8476E-005</td>
<td>1</td>
<td>2.8476E-005</td>
<td>12.2545</td>
<td>0.00255309 significant</td>
</tr>
<tr>
<td>C-Pressure</td>
<td>2.8476E-005</td>
<td>1</td>
<td>2.8476E-005</td>
<td>12.2545</td>
<td>0.00255309 significant</td>
</tr>
<tr>
<td>Residual</td>
<td>4.18280E-005</td>
<td>18</td>
<td>2.32378E-006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>2.88465E-005</td>
<td>13</td>
<td>2.21896E-006</td>
<td>0.85464</td>
<td>0.625119 not significant</td>
</tr>
<tr>
<td>Pure Error</td>
<td>1.29815E-005</td>
<td>5</td>
<td>2.59630E-006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>7.03046E-005</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The increase in electrical conductivity could be due to better debundling of the carbon nanotubes in the suspension. Another possibility is that the pressure increase causes the sonicator tip to rapidly deposit titanium particles onto the Buckypaper. Previous studies conducted by Rodriguez have shown that with an increase in pressure the replaceable titanium sonicator tip degrades faster than under no pressure systems(2). Titanium has an electrical conductivity of 238.1 S/cm, which even in small amounts could have caused the increase from a low electrical conductivity of 48 S/cm to a high electrical conductivity of 83.3 S/cm.

7.3 Mechanical Testing

Mechanical testing was conducted as stated in section 5.4.3. For each disk three measurements were taken and tested for modulus, tensile strength and failure strain. A typical stress-strain curve is shown in Figure 31. The graph also includes static force applied to the sample.
Figure 31: A typical stress-strain curve from the DMA of SWNT Buckypaper.

7.3.1 Tensile Strength

The tensile strength of the Buckypaper was determined to be related to the values of amplitude and pressure.
The ANOVA table, Table 5, was conducted for the values of strength $^2$. The R=0.492, the Adj R$^2$=0.4323, the Pred R=0.2677. The model reliability is less than that for electrical conductivity, but still acceptable for experimental data. The governing equation shows that as:

Equation 3: Strength model from 90 mm sample disk experiment

$$Strength^2 = 256.476 - 2.16135 \cdot Amplitude + 4.37247 \cdot Pressure$$
As pressure increases the strength increases as well, whereas while amplitude increase the strength decreases. If the pressure were increasing and debundling the nanotubes they would have a higher aspect ratio and possibly higher strength properties. The increase in amplitude may cause cutting or shortening of the nanotubes which could make a weaker network and cause the nanotubes to separate faster and allow for the easy breaking of the Buckypaper.

7.3.2 Strain

The strain of the Buckypaper was obtained for each of the samples. The blue bars represent the average value for strain, while the error bars represent the standard deviation among the three measurements taken for each sample disk.
The ANOVA table, Table 6, shows no significant factors for determining the strain of the Buckypaper. The suggested quadratic model yielded no p-values less than 0.1, indicating that no reliable model exists for determining strain based on the current data.
One attribute for a lack of model could be high noise during the sample preparation process and installation of the samples on the machine test fixture, which usually has large variation from sample to sample. Hence the results showed high noise.

7.3.3 Modulus
The modulus of the Buckypaper was obtained for each of the samples. The blue bars represent the average value for the modulus, while the error bars represent the standard deviation among the three measurements taken for each sample disk.
The ANOVA table, shown in Table 7, shows no significant factors for determining the modulus of the Buckypaper samples. The suggested quadratic model yielded no p-values less than 0.1, indicating that no model exists for determining modulus based on the experimental data.
Table 7: ANOVA table for modulus of 90 mm sample disks.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2.10701E+006</td>
<td>9</td>
<td>23411.3</td>
<td>1.35816</td>
<td>0.318892</td>
</tr>
<tr>
<td>A-Power</td>
<td>527120.</td>
<td>1</td>
<td>527120.</td>
<td>3.05799</td>
<td>0.110912</td>
</tr>
<tr>
<td>B-Flow rate</td>
<td>378312.</td>
<td>1</td>
<td>378312.</td>
<td>2.19470</td>
<td>0.169294</td>
</tr>
<tr>
<td>C-Pressure</td>
<td>57363.0</td>
<td>1</td>
<td>57363.0</td>
<td>0.332780</td>
<td>0.576781</td>
</tr>
<tr>
<td>AB</td>
<td>207363.</td>
<td>1</td>
<td>207363.</td>
<td>1.20298</td>
<td>0.298437</td>
</tr>
<tr>
<td>AC</td>
<td>248507.</td>
<td>1</td>
<td>248507.</td>
<td>1.44166</td>
<td>0.257539</td>
</tr>
<tr>
<td>BC</td>
<td>387780.</td>
<td>1</td>
<td>387780.</td>
<td>2.24963</td>
<td>0.164539</td>
</tr>
<tr>
<td>A²</td>
<td>46853.8</td>
<td>1</td>
<td>46853.8</td>
<td>0.271814</td>
<td>0.613467</td>
</tr>
<tr>
<td>B²</td>
<td>100494.</td>
<td>1</td>
<td>100494.</td>
<td>0.582998</td>
<td>0.462773</td>
</tr>
<tr>
<td>C²</td>
<td>203725.</td>
<td>1</td>
<td>203725.</td>
<td>1.18187</td>
<td>0.302484</td>
</tr>
<tr>
<td>Residual</td>
<td>1.72375E+006</td>
<td>10</td>
<td>172375.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>866018.</td>
<td>5</td>
<td>173204.</td>
<td>1.00966</td>
<td>0.495919 not significant</td>
</tr>
<tr>
<td>Pure Error</td>
<td>857730.</td>
<td>5</td>
<td>171546.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>3.83076E+006</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.4 SEM image analysis

In order to determine nanostructure Scanning Electron Microscope (SEM) images were taken using the JOEL. For each sample two images were taken on either side of the sample. The ‘front’ side of the sample represents the top of the sample during filtration, while the ‘back’ represents the surface of the Buckypaper that was previously touching the filter membrane. Using the SEM images the back of the Buckypaper is fairly readily identifiable by a number of white marks. During filtration the nanotubes are embedded into the filter membrane porous structures and Buckypaper is pulled from the filter membrane for harvesting. The embedded nanotube bundles are broken apart, leaving many white marks visible in Figure 35.
In order to determine the impact the processing parameters have on the diameters of the nanotube bundles 18 tubes were measured from each image at 100,000X magnification. The front and backs were analyzed individually.

7.4.1 Front Buckypaper SEM Image Analysis

An ANOVA table, Figure 36, was created for the diameter of bundles for the frontside of the Buckypaper, showing that pressure has an impact. At low pressures the bundle diameter is decreased, while at higher pressures the bundle diameter increases, indicated by the equation:

$$SEM\ Front = 10.4098 - 0.368130 \times \text{Pressure} + 0.0174035 \times \text{Pressure}^2$$
The $R^2$ for this model is 0.352376, the Adjusted $R^2$ is 0.259858, and the Predicted $R^2$ is 0.140328. The $R^2$ values are fairly low and could possibly be increased through more sampling of tube diameters.

### 7.4.2 Back Buckypaper SEM Image Analysis

An ANOVA table, Figure 37, was created for the diameter of bundles for the backside of the Buckypaper, showing that amplitude has an impact. Amplitude increases cause a decrease in bundle diameter for the backside of the BP, indicated by the equation:

$$\text{SEM Back} = 10.6770 - 0.0311692 \times \text{Amplitude}$$

The $R^2$ for this model is 0.4264, the Adjusted $R^2$ is 0.381660, and the Predicted $R^2$ is 0.279442. The $R^2$ values are higher than for the frontside of the SEM images but could possibly be increased through more sampling of tube diameters.

### 7.4.3 SEM Image Analysis Conclusion

The two models show different impact parameter, amplitude for frontside and pressure for backside. This could indicate that the impact of amplitude is rapidly reduced while the effects of pressure endure for nanotube re-agglomeration, as the backside of the Buckypaper was formed first and the front side of the Buckypaper was filtered approximately 2 hours after starting. However, due to the limited data the accuracy of the models is fairly low. Improved image analysis software and sufficient sampling of tubes are needed to further improve accuracy.
8. INTERACTIVE ANALYSIS OF RESPONSES

Previously no study of Buckypaper contained such comprehensive measurements for all samples. A correlation between electrical conductivity properties, mechanical properties, and nanostructure properties has been examined from the 20 sample disks. All values were normalized by dividing each value by its corresponding average. There is no notable trend for correlation of different properties.

![Figure 38: The Modulus, Strength, and Electrical data normalized averages for sample disks.](image)

Possible correlations between Modulus, Strength, Strain, Electrical Conductivity, and Thickness were also researched by plotting each parameter against the other parameters in a scatter plot. The only scatter plot that showed a relationship between properties was that of
strength and strain. The scatter plot, Figure 39, shows an increased strength value appears to yield a higher strain value. It is reasonable that high strength nanotube network can ensure large deformation, hence leads to higher failure strength.

![Scatterplot of Strain vs Strength](image)

*Figure 39: A scatter plot of Strain vs Strength for sample disks.*
9. LONG SWNT CBP PRODUCTION USING 1.5” FILTER

9.1 Production Parameters

In order to prove the feasibility of producing 1.5” continuous Buckypaper using the improved filter a long piece of Buckypaper was produced. Optimal processing parameters for the Buckypaper were chosen. The long CBP was successfully harvested and tested. An image of the completed strip of CBP is shown in Figure 40.

Figure 40: Image of long CBP.

9.2 Processing Rate

The normalized filtration time for each step is shown in Figure 41.

Figure 41: Normalized filtration time scatter plot for long CBP.
9.2 Thickness Properties

Three measurements were taken across the width of the paper at 2” intervals of the sample. The average thickness for the CBP was repeatable, with a relatively small standard deviation. A scatter plot of the normalized thickness values of the CBP is shown in Figure 42.

![Normalized Thickness Scatterplot](image)

Figure 42: Normalized thickness scatter plot for long CBP.

9.3 Mechanical Properties

Eight measurements were taken using the DMA to obtain mechanical properties; the normalized results are shown in Figure 43.

![Normalized Strength of CBP](image)

Figure 43: Normalized strength of long CBP.
A model was undeterminable for the modulus, but the modulus values for this sample CBP showed great improvement from the preliminary CBP sample. The bar chart in Figure 44 shows the normalized values for modulus with the error bars representing the normalized standard deviation between the three measurements taken at each location.

![Normalized Modulus of CBP](image)

Figure 44: Normalized modulus of long CBP.

The strain did not have a prediction model. Values for strain do not show an increase from the preliminary CBP. The values for strain are shown in Figure 45 with the error bars representing the standard deviation between the samples measured at each location.
The tensile strength and modulus values increased and showed more consistency than the preliminary CBP measurements. The values for tensile strength are considerably higher than predicted, indicating that transferring the processing parameters from the 90 mm sample disks to the CBP filter are not exactly the same for mechanical properties. The unpredicted modulus increase compared to the 90 mm disk samples was possibly due to process consistency improvement.

9.4 Electrical Properties

Thirteen measurements were taken using the 4 wire test method to obtain electrical conductivity.

The electrical conductivity measurement normalized values are shown in Figure 46 with the error bars representing the normalized standard deviation between the four samples taken at each location.
The electrical conductivity showed more consistency than the preliminary CBP measurements. The values for electrical conductivity are greatly improved but are considerably higher than predicted from the model prediction.

9.5 Conclusions for long CBP Sample Production

The production of the long of CBP provided further evidence that continuous Buckypaper production is feasible. The increases in values for electrical conductivity and strength properties confirmed the relationship between the processing parameters displayed in the 90 mm sample disk experimental study.
10. FINAL LONG SWNT CBP PRODUCTION

10.1 Processing Parameters
The final strip of CBP using SWNT was successfully produced.

10.2 Processing Rate
The average filtration time for each step was constant, with a small standard deviation. The normalized filtration rate is shown in Figure 47.

\[ \text{Normalized Filtration Time per Step} \]

```
0  0.5  1  1.5  2  2.5
0  5  10  15  20  25  30

Foot Location
```

Figure 47: Scatter plot for filtration time of the final long CBP.

10.3 Conclusions for the final CBP Production
The feasibility of widening the CBP filter was previously proven. The production of the long strip of CBP at a noticeable increase proves that industrial scale manufacturing of Buckypaper is feasible by designing and fabricating filters with large filtration area.
11. CONCLUSIONS

This research successfully revealed correlations between the processing parameters of pressure and amplitude with the response variables of electrical conductivity and strength. Models for the processing parameters and properties were created. From the 90 mm sample disk experiment processing parameters were established for CBP manufacturing. The implemented processing parameters were utilized to produce a long CBP sample that yielded an average of 20% increase in electrical conductivity, a 50% increase in modulus, and a 68% increase in strength values from the initially tested sample CBP sample. The consistency of the Buckypaper was shown to be maintained throughout the sample of CBP for mechanical and electrical properties. Implementation of improvements to the original CBP filter, including replacing the pneumatic motor with an electronic motor and using a new vacuum system, resulted in increases in consistency and production rate and allowed for the monitoring of suspension deposited onto the filter membrane. Improved production rate was demonstrated.

In addition to improving the original CBP filter this research also proved that filtration rate can be increased without sacrifice to CBP integrity. The large filter further builds upon the industrial use application by incorporating a washing station, allowing for a reduction in post production time associated with surfactant removal. To demonstrate the capabilities of the filter long strips of CBP were produced with an improved production rate. Consistency for filtration time was maintained throughout the production of the strips of CBP.
12. FUTURE WORK

For future research a flow meter should also be implemented to have an accurate value for the flow rate parameter. The actual flow rate could then be used to determine an existing relationship between flow rate and responses that was previously dependent upon pressure and amplitude. An experiment varying the processing parameters and testing the mechanical and electrical properties should be conducted using the CBP filters, rather than 90 mm disks to obtain a more accurate model relating processing parameters and response variables for CBP and to further improve upon the electrical and mechanical properties. To further industrial application development in-line washing experiments should be conducted on the CBP and an automatic winding mechanism should be added to the end of the CBP filter to reduce post-production processing time. To maintain a lower cost and allow for true continuous production the implementation of a reusable filter membrane should be examined to be use as a continuous conveyor belt rather than a disposable, discrete roll of membrane.
REFERENCES


BIOGRAPHICAL SKETCH

Jasmine Pualani Young

Jasmine Pualani Young graduated with her Bachelor’s degree in Industrial and Manufacturing Engineering in the spring of 2007. Under the advisement of Professor Richard Liang she obtained her Master’s degree in the summer of 2009 also in the Industrial and Manufacturing Engineering department. Shortly after completing her thesis research she began working at Raytheon Missile Systems.